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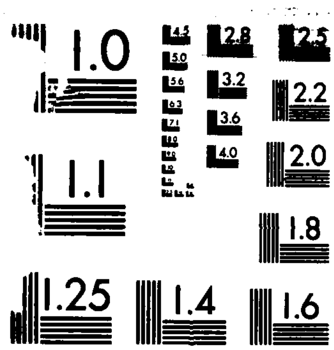

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J_{Ic} TESTING USING ARC-TENSION SAMPLES

J. A. KAPP

W. J. BILINSKY

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
CLOSE COMBAT ARMAMENTS CENTER
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J_{Ic} was determined in two materials (6061-T651 aluminum and ASTM A-723 grade 1, class 4 pressure vessel steel) using arc-tension (A(T)) and compact tension (C(T)) samples. The J-R curves were determined by using both the multispecimen method and the compliance unloading method. J was determined for the A(T) specimen by the Merkle-Corten method of analysis as modified by Clarke and Landes. A correction factor was included to account for the tensile loading

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20. ABSTRACT (CONT'D)

component, and both the plastic and elastic components of J were necessary when using the A(T) sample. With the proper formulas for J in the A(T) sample, the same J-R curves were determined in both materials using either A(T) or C(T) samples. This preliminary study suggested that the A(T) sample was totally adequate for J_{Ic} testing and should be included in subsequent versions of ASTM Method E-813 on J_{Ic}, A Measure of Fracture Toughness.

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INTRODUCTION

Fracture toughness, whether measured as K_{Ic} or J_{Ic} is a valuable measurement of a material's tolerance of pre-existing defects and many engineering applications. The present method for determining J_{Ic} (ASTM Method E-813 on J_{Ic}, A Measure of Fracture Toughness) allows J_{Ic} to be measured by either a compact tension (C(T)) sample or a three-point bend sample (SE(B)). Sometimes it is difficult to obtain specimens of these geometries from certain structural components such as cylindrical pressure vessels. The arc-tension (A(T)) sample is easily obtained from such cylindrical components. This report summarizes the results of an initial study into the feasibility of using A(T) samples for J_{Ic} testing.

CALCULATION OF J FOR A(T) SAMPLES

The A(T) sample (Figure 1) encompasses a large range of possible geometries. This is due to the variability of R_2, R_1, and X. For this sample to be of the most use, restrictions on R_2 and R_1 cannot be allowed, but restricting X in J testing should cause few difficulties. X is made variable in K testing mainly for load efficiency, but if substantial plasticity is allowed as in J testing, load efficiency is not as important. Thus, we restrict our thinking to A(T) samples with $X = 0$, which has the further experimental advantage in displacement measurement as the load line intersects the crack mouth.

To determine J for the arc-tension sample, we proceed in the manner outlined by Merkle and Corten (ref 1) as modified by Clarke and Landes (ref 2). Under fully plastic conditions on the uncracked ligament, the load-displacement trace is idealized as shown in Figure 2, and J is (Equation 9, Reference 2):

$$J = \frac{2}{bB}\left[\frac{1+\alpha}{1+\alpha^2} - \alpha\frac{(1-2\alpha-\alpha^2)}{(1+\alpha^2)^2}\right] A_T$$

$$+ \frac{2\alpha}{bB}\frac{(1-2\alpha-\alpha^2)}{(1+\alpha^2)^2} P^*\delta_T + G$$

$$- \frac{2}{bB}\left[\frac{1+\alpha}{1+\alpha^2} + \alpha\frac{(1-2\alpha-\alpha^2)}{(1+\alpha^2)^2}\right] A_e \qquad (1)$$

where b and B are as shown in Figure 1; A_T, P^*, δ_T and A_e are from Figure 2; G is the elastic energy release rate, and

$$\alpha = 2((a/b)^2 + a/b + 1/2)^{1/2} - 2(a/b + 1/2) \qquad (2)$$

where a is the crack length as shown in Figure 1.

Equation (1) is too cumbersome to be useful experimentally. The first step in simplifying the equation is to assume that the higher order terms involving A_T and $P^*\delta_T$ cancel:

$$J = \frac{2A_T}{bB}\frac{1+\alpha}{1+\alpha^2} + G - \frac{2A_e}{bB}\left[\frac{1+\alpha}{1+\alpha^2} + \frac{\alpha(1-2\alpha-\alpha^2)}{(1+\alpha^2)^2}\right] \qquad (3)$$

It is convenient to represent G in terms of the elastic area A_e. It can be shown that (refs 1,2):

---

[1]Merkle, J. G. and Corten, H. T., J. of Pressure Vessel Technology, Trans. ASME, Vol. 96, November 1974, pp. 286-292.

[2]Clarke, G. A. and Landes, J. D., Journal of Testing and Evaluation, Vol. 7, No. 5, September 1979, pp. 264-269.

$$G = \left[\frac{k(1-a/w)Y^2}{EB}\right]\frac{2A_e}{Bb} \tag{4}$$

where

$$Y = \frac{KB\sqrt{w}}{P}$$

and k is the elastic stiffness of the specimen or the initial slope of the load-displacement record, K is the stress intensity factor, and E is the elastic modulus. Finally, we can write Eq. (3) in the simple form

$$J = \lambda_1 \frac{2A_T}{Bb} + \lambda_2 \frac{2A_e}{Bb} \tag{5}$$

$$\lambda_1 = \frac{1+\alpha}{1+\alpha^2} \tag{6}$$

$$\lambda_2 = \frac{k(1-a/w)Y^2}{EB} - \left(\lambda_1 + \frac{\alpha(1-2\alpha-\alpha^2)}{(1-\alpha^2)\alpha^2}\right) \tag{7}$$

These equations are the same equations that were developed for the C(T) sample (refs 1,2). However, in the C(T) sample when a/w is 0.5 or larger, λ_2 is negligible. This is not the case with the arc-tension sample. We evaluate λ_2 by using wide-range expressions fit to numerical stress analysis results (refs 3,4).

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[1]Merkle, J. G. and Corten, H. T., J. of Pressure Vessel Technology, Trans. ASME, Vol. 96, November 1974, pp. 286-292.
[2]Clarke, G. A. and Landes, J. D., Journal of Testing and Evaluation, Vol. 7, No. 5, September 1979, pp. 264-269.
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$$Y = \frac{KB\sqrt{w}}{P} = [3\ x/w + 1.9 + 1.1\ a/w][1 + 0.25(1 - a/w)^2(1-R_1/R_2)]f(a/w) \quad (8)$$

$$f(a/w) = ((a/w)^{1/2}/(1-a/w)^{3/2})(3.74 - 6.30\ a/w + 6.32(a/w)^2 - 2.43(a/w)^3)$$

$$k = \frac{P}{\delta} = \frac{EB(1-a/w)^2}{(2\ x/w + 1 + a/w)F(a/w,r_1/r_2)} \quad (9)$$

$$F(a/w,R_1/R_2) = [0.34 + 13.75\ a/w - 12.67(a/w)^2 + 6.47(a/w)^2$$
$$+ (1-a/w)^{0.05}(1-R_1/R_2)(0.8-0.5\ R_1/R_2)]$$

To compare the quantities necessary to determine J, it is convenient to use the following notation:

$$\lambda_1 = \frac{1+\alpha}{1+\alpha^2}$$

$$\lambda^* = \frac{\alpha(1-2\alpha-\alpha^2)}{(1+\alpha^2)^2}$$

$$\lambda_J = \lambda_1 + \lambda^*$$

$$\lambda_e = \frac{k(1-a/w)Y^2}{EB}$$

These quantities are computed for various R_1/R_2 and comparisons made in Table I. The tabulation shows that in the crack length range important to J_{Ic} testing $a/w > 0.45$, λ_2 is not negligible. Indeed, should A_e be a significant portion of A_T, neglecting to account for this elastic portion of J would introduce errors approaching 20 percent. Therefore, unlike J_{Ic} testing with C(T) samples, we must include the contribution of A_e to obtain an accurate measurement of J when using A(T) specimens.

TABLE I. COMPARISON OF THE QUANTITIES USED TO DETERMINE J FOR THE ARC-TENSION, X/W = 0 SAMPLE

$R_1/R_2 = 0.91$						
a/w	λ_1	λ^*	λ_J	λ_e	λ_e/λ_J	λ_2
0.3000	1.1773	0.0963	1.2736	1.8404	1.4450	0.5668
0.3500	1.1674	0.1013	1.2687	1.7164	1.3528	0.4476
0.4000	1.1565	0.1034	1.2600	1.6092	1.2772	0.3492
0.4500	1.1448	0.1029	1.2477	1.5183	1.2169	0.2706
0.5000	1.1325	0.1000	1.2325	1.4423	1.1703	0.20[illegible]9
0.5500	1.1196	0.0950	1.2146	1.3793	1.1356	0.1647
0.6000	1.1063	0.0882	1.1946	1.3271	1.1110	0.1326
0.6500	1.0929	0.0800	1.1728	1.2835	1.0944	0.1107
0.7000	1.0793	0.0705	1.1498	1.2459	1.0837	0.0962
0.7500	1.0657	0.0600	1.1257	1.2120	1.0766	0.0863
0.8000	1.0522	0.0488	1.1009	1.1790	1.0709	0.0780
$R_1/R_2 = 0.67$						
a/w	λ_1	λ^*	λ_J	λ_e	λ_e/λ_J	λ_2
0.3000	1.1773	0.0963	1.2736	1.8850	1.4800	0.6114
0.3500	1.1674	0.1013	1.2687	1.7501	1.3794	0.4814
0.4000	1.1565	0.1034	1.2600	1.6332	1.2962	0.3732
0.4500	1.1448	0.1029	1.2477	1.5338	1.2293	0.2861
0.5000	1.1325	0.1000	1.2325	1.4505	1.1769	0.2182
0.5500	1.1196	0.0950	1.2146	1.3814	1.1373	0.1668
0.6000	1.1063	0.0882	1.1946	1.3241	1.1085	0.1296
0.6500	1.0929	0.0800	1.1728	1.2763	1.0883	0.1035
0.7000	1.0793	0.0705	1.1498	1.2355	1.0746	0.0857
0.7500	1.0657	0.0600	1.1257	1.1991	1.0652	0.0734
0.8000	1.0522	0.0488	1.1009	1.1644	1.0576	0.0634

TABLE I. COMPARISON OF THE QUANTITIES USED TO DETERMINE J

FOR THE ARC-TENSION, X/W = 0 SAMPLE (CONT'D)

$R_1/R_2 = 0.5$						
a/w	λ_1	λ^*	λ_J	λ_e	λ_e/λ_J	λ_2
0.3000	1.1773	0.0963	1.2736	1.8987	1.4908	0.6251
0.3500	1.1674	0.1013	1.2687	1.7591	1.3865	0.4904
0.4000	1.1565	0.1034	1.2600	1.6375	1.2997	0.3776
0.4500	1.1448	0.1029	1.2477	1.5339	1.2294	0.2862
0.5000	1.1325	0.1000	1.2325	1.4469	1.1740	0.2145
0.5500	1.1196	0.0950	1.2146	1.3746	1.1318	0.1600
0.6000	1.1063	0.0882	1.1946	1.3147	1.1006	0.1201
0.6500	1.0929	0.0800	1.1728	1.2648	1.0784	0.0919
0.7000	1.0793	0.0705	1.1498	1.2223	1.0631	0.0725
0.7500	1.0657	0.0600	1.1257	1.1846	1.0524	0.0590
0.8000	1.0522	0.0488	1.1009	1.1493	1.0439	0.0484
$R_1/R_2 = 0.4$						
a/w	λ_1	λ^*	λ_J	λ_e	λ_e/λ_J	λ_2
0.3000	1.1773	0.0963	1.2736	1.9007	1.4923	0.6270
0.3500	1.1674	0.1013	1.2687	1.7593	1.3867	0.4906
0.4000	1.1565	0.1034	1.2600	1.6357	1.2982	0.3757
0.4500	1.1448	0.1029	1.2477	1.5302	1.2263	0.2824
0.5000	1.1325	0.1000	1.2325	1.4414	1.1696	0.2090
0.5500	1.1196	0.0950	1.2146	1.3676	1.1260	0.1530
0.6000	1.1063	0.0882	1.1946	1.3064	1.0936	0.1118
0.6500	1.0929	0.0800	1.1728	1.2554	1.0704	0.0826
0.7000	1.0793	0.0705	1.1498	1.2121	1.0543	0.0624
0.7500	1.0657	0.0600	1.1257	1.1740	1.0429	0.0483
0.8000	1.0522	0.0488	1.1009	1.1385	1.0341	0.0375

Although λ_2 could be calculated from Eqs. (8) and (9), significant computation is involved. Noting that λ_2 is virtually independent of R_1/R_2, a simple polynomial in a/w can be found from which λ_2 is more easily determined. Using least squares the polynomial is:

$$\lambda_2 = 1.919 - 6.235(a/w) + 6.935(a/w)^2 - 2.557(a/w)^3 \qquad (10)$$

In the range of $0.5 < a/w < 0.6$, Eq. (10) agrees with the computed values of λ_2 within about five percent for R_1/R_2 between 0.4 and 0.9.

EXPERIMENTAL PROCEDURE

J_{Ic} tests were performed on a pressure vessel steel and an aluminum alloy using both A(T) and C(T) samples. Also, both methods for determining crack growth outlined in ASTM Method E-813 on J_{Ic}, A Measure of Fracture Toughness, (compliance unloading and fracture surface measurement) were used. The aluminum alloy used was 6061-T651 supplied in rolled sheet form 0.5 inch (1.27 cm) thick. Specimens were obtained such that the L-T direction was tested. The compact tension samples were of the standard geometry with thickness (B) of 0.5 inch (1.27 cm). A(T) samples were produced such that the outside radius R_2 was 2.0 inches (5.08 cm) and the inside radius R_1 was 1.0 inch (2.54 cm). The pressure vessel steel used was ASTM A-723 grade 1, class 4. Specimens were obtained from a long hollow cylindrical forging which had an outside radius of 4.6 inches (11.7 cm) and an inside radius of 1.9 inches (4.8 cm). Samples were obtained in the C-R orientation with through thickness, B, dimension of 1.35 inches (3.4 cm). After testing the A(T) specimens, C(T) samples were machined from one of the broken halves of the A(T) sample. The largest possible sample was obtained, one with through thickness (B) of 0.8 inch (2.3 cm).

RESULTS AND DISCUSSION

The results of the testing of these samples appear in Figures 3 through 6. The results from the pressure vessel steel (Figures 3 and 4) suggest very little difference in J_{Ic} by using different samples. With the multispecimen method (Figure 3), the slope of the resistance curve is the same for either sample, but the intersection with the blunting line is somewhat greater when using compact tension samples. Although J_{Ic} appears to be affected by the specimen, the difference between the two test results can be easily attributed to scatter. With compliance unloading (Figure 4), more variation is evident. The two resistance curves from the arc-tension samples are approximately parallel but offset such that different values of J_{Ic} were obtained. Comparing these to the two curves generated using compact tension samples, we find that the least squares fit to these data gives a slope which is substantially steeper than those obtained with arc-tension samples. The J_{Ic} values obtained from these tests are very close (76 kJ/m^2 and 81 kJ/m^2) and compare very favorably with one of the two arc-tension sample J_{Ic} measurements. Again, one might consider the differences as the result of using different specimen geoemtries, but it is safe to account for these differences as material scatter.

Comparing the results of testing the 6061-T651 aluminum alloy also shows little or no difference between arc-tension and compact tension samples. With multispecimen testing (Figure 5), essentially the same resistance curve was obtained using either sample geometry. The least squares lines fit to these data gives a small difference in slope and somewhat different J_{Ic} value, but again these differences are material property scatter. With compliance

unloading, similar to the steel results, more scatter was observed. All of the resistance curves had essentially the same slopes, but J_{Ic} varied a great deal with these specimens. The two compact tension J_{Ic} values agreed very well, but the two arc-tension samples differed substantially, although the average of the two compact tension values compared very well with the average of the two arc-tension values.

For further comparison, the J_{Ic} results are presented in Table II. For each material and specimen type, the three J_{Ic} values generated (one by the multispecimen method and two by the compliance unloading method) are treated as a single statistical population. The mean value and standard deviation are given for each population. It is clear that the mean value of J_{Ic} from the A(T) and C(T) specimens of pressure vessel steel is essentially the same, although there seems to be somewhat more scatter generated when the A(T) specimens are used. The reason for the scatter cannot be established at this time. Further testing would be required to determine if the difference is due to specimen geometry or natural material scatter. The same can be stated for the aluminum. Reasonable agreement between the mean values of J_{Ic} from either specimen type was observed, but as in the case of the aluminum tests, scatter is much greater when A(T) samples are used than when C(T) samples are used. Again, whether the cause of the scatter is the specimen geometry or material related, it would have to be determined by testing a larger number of specimens.

Regardless of the reasons for increased scatter in the J_{Ic} results from A(T) samples versus C(T) samples, it is encouraging that the mean values of J_{Ic} for two different materials are about the same using both A(T) and C(T)

samples. Further testing should be performed, perhaps in coordination with Task Group E24.08.04 as a laboratory round robin to establish if the A(T) sample should be included in later versions of ASTM Method E-813 on J_{Ic}, A Measure of Fracture Toughness.

TABLE II. STATISTICAL COMPARISON OF J_{Ic} MEASURED WITH BOTH A(T) AND C(T) SAMPLES

		J_{Ic} (kJ/m^2)	
Material		A(T)	C(T)
Pressure Vessel Steel		75	86
		94	76
		79	81
	Mean	82.6	81.0
	Standard Deviation	10.0	5.0
6061-T651 Aluminum		7.9	9.4
		5.5	8.6
		16.1	5.9
	Mean	9.8	8.0
	Standard Deviation	5.56	1.83

SUMMARY AND CONCLUSIONS

Analyses and tests were performed to determine the applicability of using A(T) samples for J_{Ic} testing. The analysis showed that to determine J for these specimens, a more involved calculation is necessary, namely, J must be broken into its elastic and plastic components. Two areas under the load displacement curve must be measured. This is more complex than the analysis involved with compact tension samples, but the additional amount of analysis involved should not restrict the use of A(T) samples. J_{Ic} measurements were made using both compact tension and arc-tension samples. The A(T) sample should be considered as an alternative specimen in future versions of ASTM Method E-813 on J_{Ic}, A Measure of Fracture Toughness.

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3. Kapp, J. A., Newman, J. C., Jr., and Underwood, J. H., Journal of Testing and Evaluation, Vol. 8, No. 6, November 1980, pp. 314-317.

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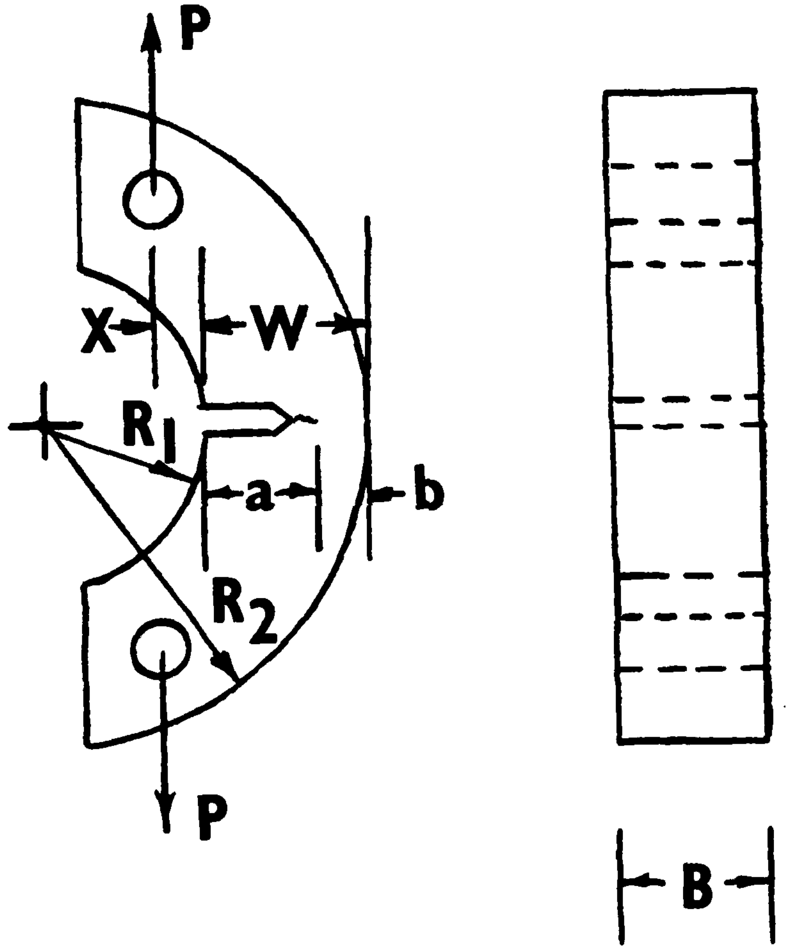

Figure 1. The arc-tension sample.

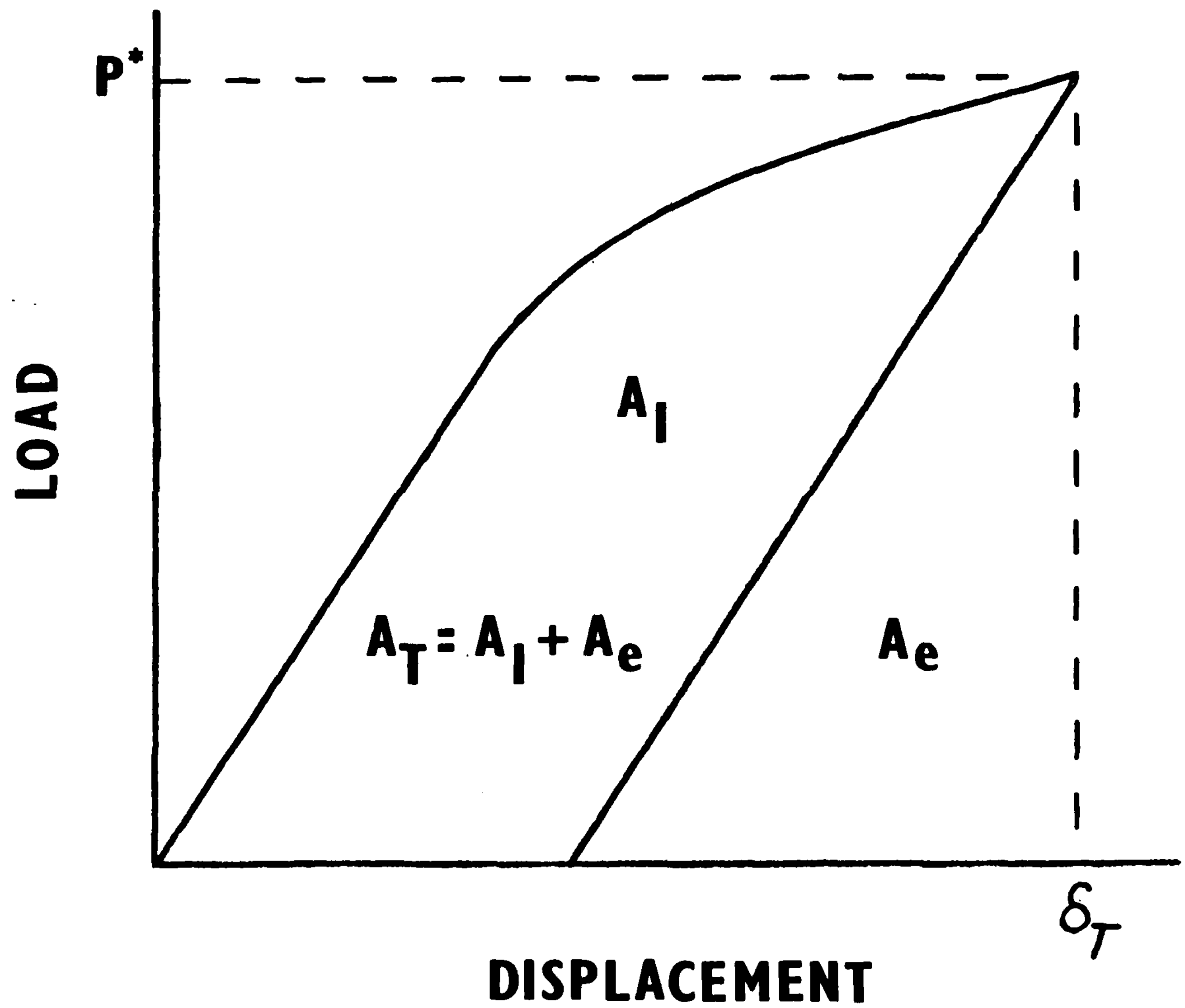

Figure 2. Idealized elastic-plastic load-displacement trace.

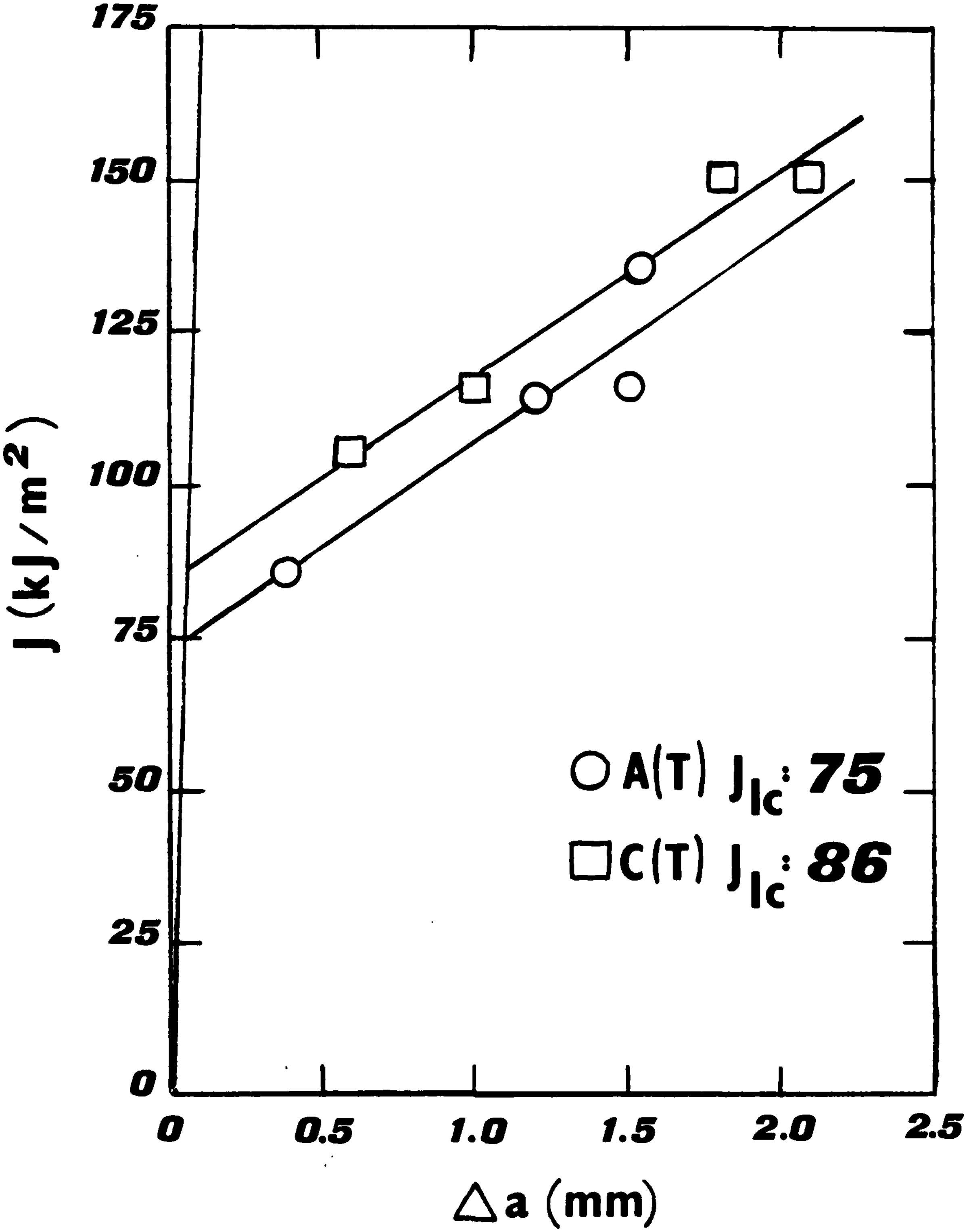

Figure 3. Multispecimen J-R curves for A-723 pressure vessel steel.

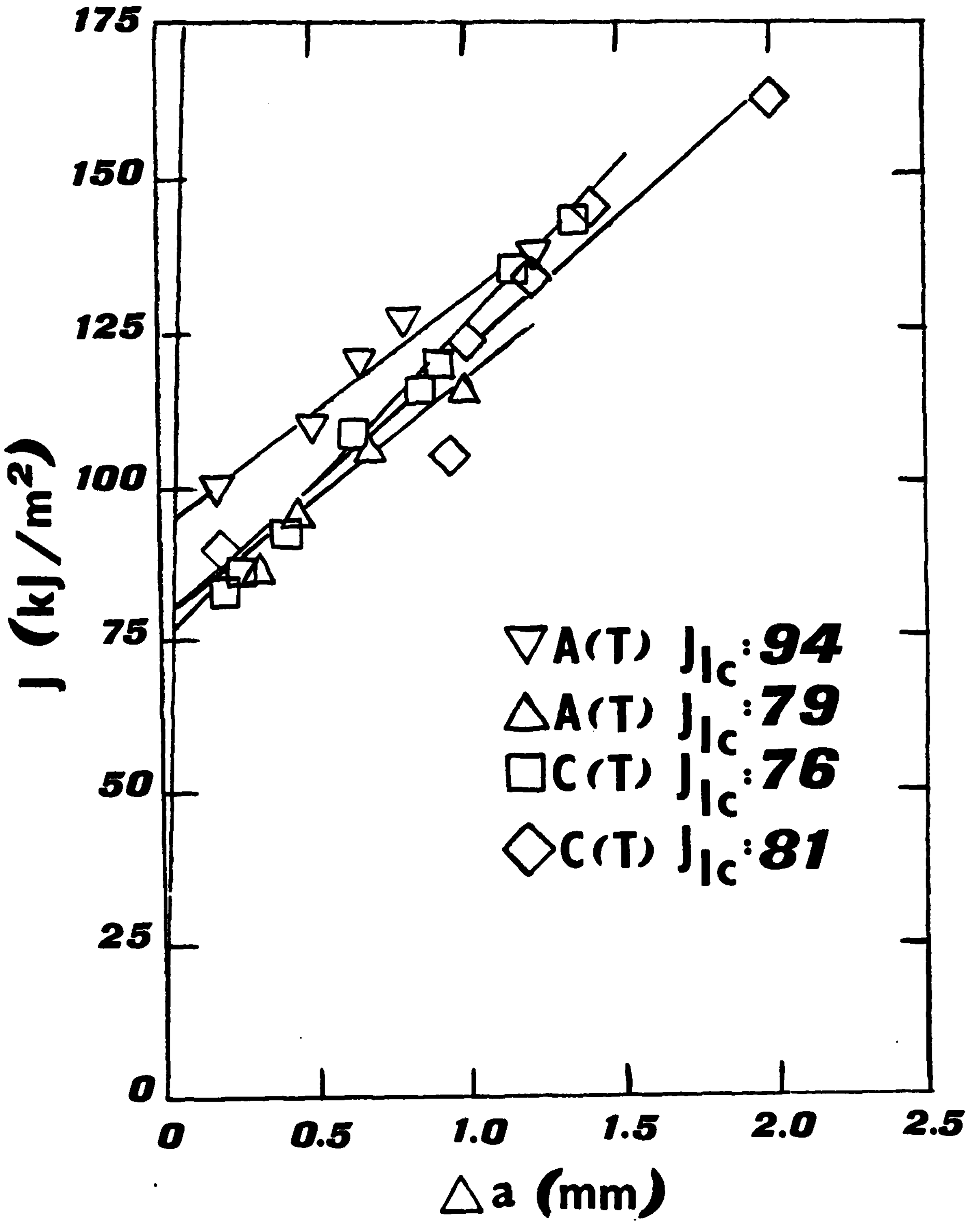

Figure 14. Compliance unloading J-R curves for A-723 pressure vessel steel.

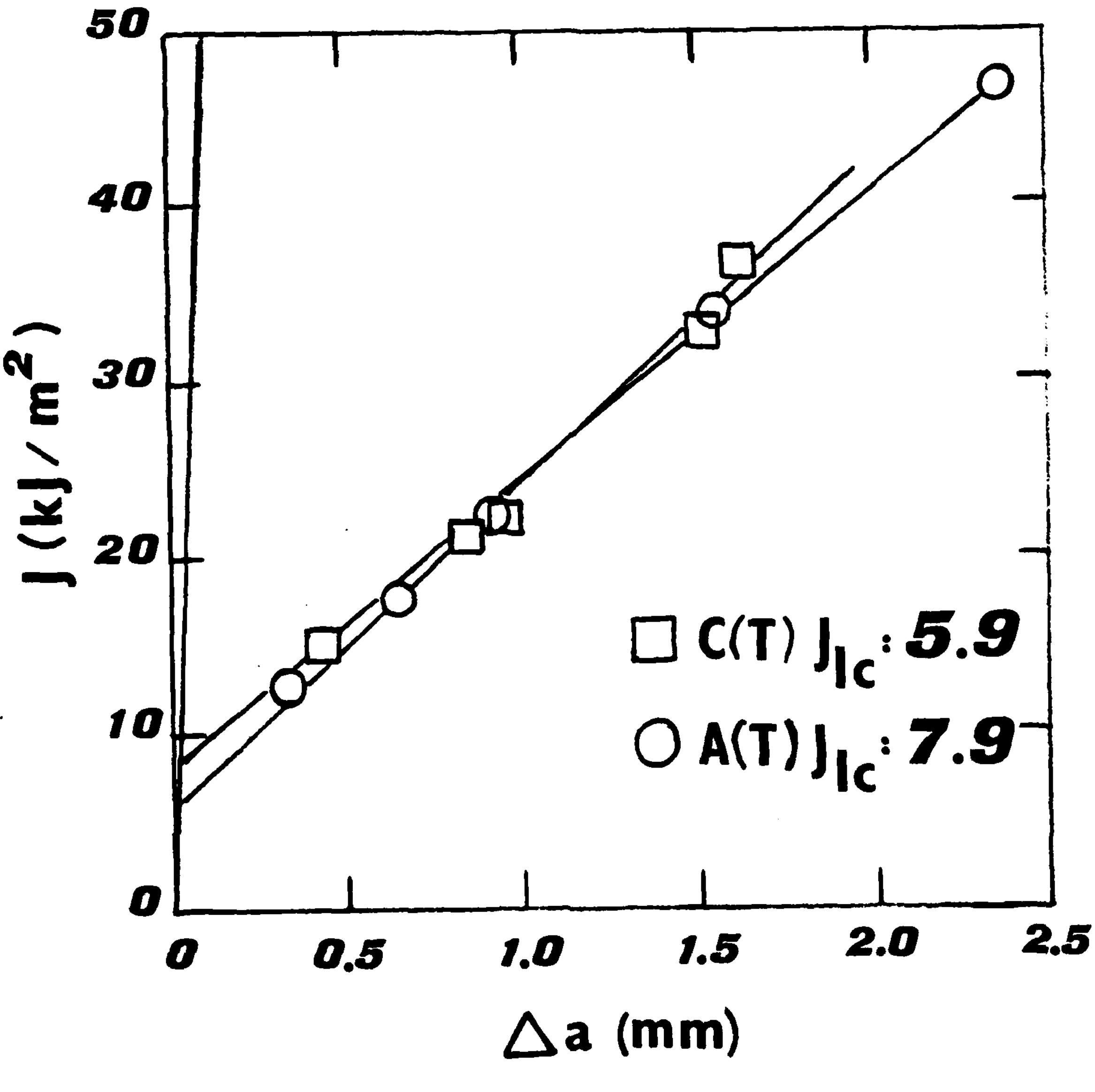

Figure 5. Multispecimen J-R curves for 6061-T651 aluminum.

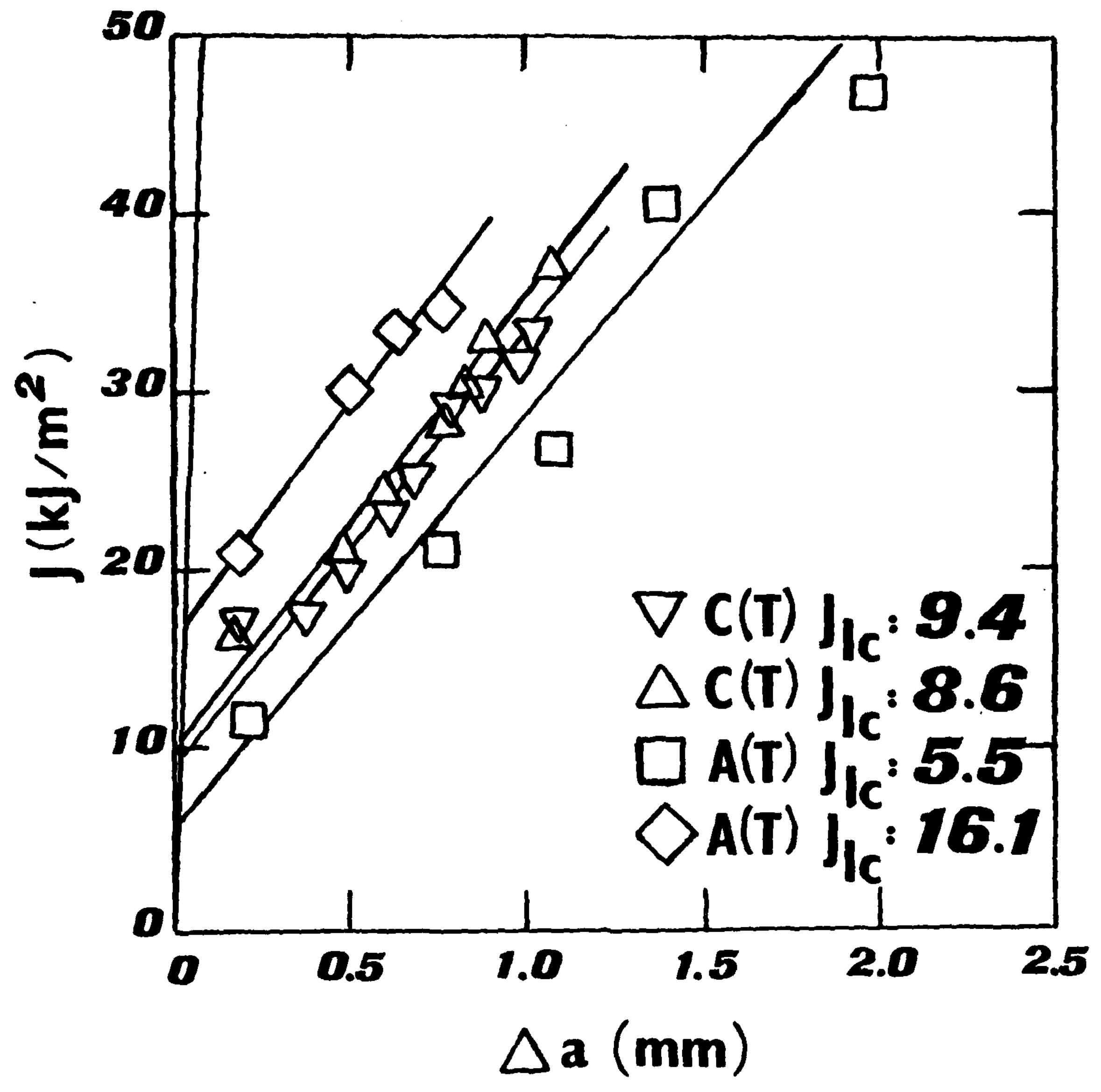

Figure 6. Compliance unloading J-R curves for 6061-T651 aluminum.

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